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Market penetration of ethanol

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ABSTRACT

This research examines in detail the technology and economics of substituting ethanol for gasoline. This endeavor examines three issues. First, the benefits of ethanol/gasoline blends are examined, and then the technical problems of large-scale implementation of ethanol. Second, ethanol production possibilities are examined in detail from a variety of feedstocks and technologies. The feedstocks are the starch/sugar crops and crop residues, while the technologies are corn wet mill, dry grind, and lignocellulosic fermentation. Examining in detail the production possibilities allows the researchers to identity the extent of technological change, production costs, byproducts, and GHG emissions. Finally, a U.S. agricultural model, FASOMGHG, is updated which predicts the market penetration of ethanol given technological progress, variety of technologies and feedstocks, market interactions, energy prices, and GHG prices.

FASOMGHG has several interesting results. First, gasoline prices have a small expansionary impact on the U.S. ethanol industry. Both agricultural producers' income and cost both increase with higher energy prices. If wholesale gasoline is $4 per gallon, the predicted ethanol market penetration attains 53% of U.S. gasoline consumption in 2030. Second, the corn wet mill remains an important industry for ethanol production, because this industry also produces corn oil, which could be converted to biodiesel. Third, GHG prices expand the ethanol industry. However, the GHG price expands the corn wet mill, but has an ambiguous impact on lignocellulosic ethanol. Feedstocks for lignocellulosic fermentation can also be burned with coal to generate electricity. Both industries are quite GHG efficient. Finally, U.S. government subsidies on biofuels have an expansionary impact on ethanol production, but may only increase market penetration by an additional 1% in 2030, which is approximately 6 billion gallons.

Contents

Abbreviations: CAAA, Clean Air Act Amendments; DDGS, Distillers Dried Grains with Solubles; EPA, Environmental Protection Agency; FASOMGHG, Forest and Agricultural Sector Optimization Model Greenhouse Gas; GHG, greenhouse gas; GWP, Global Warming Potential; HHV, higher heating value; IPCC, International Panel on Climate Change; LHV, lower heating value; MTBE, methyl tertiary-butyl ether; USDA, United States Department of Agriculture.

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1. Introduction

Gasoline and diesel fuels are significant sources of greenhouse gas (GHG) emissions particularly carbon dioxide [76]. Such emissions contribute to the greenhouse effect and climate change. Biofuels, like ethanol and biodiesel, replace fossil fuels and reduce carbon dioxide emissions by recycling carbon from the atmosphere, thus mitigating climate change. Biofuels have the following benefits:

- Biofuels are renewable.
- Biofuels could reduce petroleum imports, improve the balance of payments, improve national energy security, and reduce the reliance on petroleum from unstable areas of the world.
- Biofuels if cheaply produced can reduce demands for fossil fuels and the growth in fossil fuel prices.
- Biofuels can offset greenhouse gas emissions plus contain oxygen that reduces emissions from hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM), and sulfur dioxide (SO_2), but tend to increase NOX emissions [1–10].
- Biofuels could create stronger demands for feedstocks, thus boosting agricultural prices and producers' incomes.

Increased ethanol production seems likely to emerge in the near future. Ethanol production rapidly expanded from about 1.7 billion gallons in 2001 to over 6 billion gallons in 2006 [11] to approximately 8–9 billion gallons in 2008. Several forces are creating a strong demand for ethanol and the rapid growth of this industry.

- The Environmental Protection Agency (EPA) phased out of methyl tertiary-butyl ether (MTBE), which is an oxygenate and a fuel additive [12].
- High petroleum and gasoline prices.
- Government mandates, such as the provisions of the Energy Independence and Security Act of 2007 [13] and the oxygenate fuel requirements.
- The public and government's concern over global warming.

Clearly, the confluence of these forces cannot be observed in today's world as we have never seen such high petroleum prices or a global trade and cap system for GHG. Consequently, we do a modeling study on ethanol penetration into the market considering

- Life-cycle and more generalized procedures estimating the GHG offsets of biofuels.
- Economic simulations of the impact of carbon dioxide equivalent prices on biofuel production.
- Alternative gasoline prices that raise agricultural production costs, but create a higher price for ethanol fuel.
- The effect of U.S. government subsidies on biofuel.
- The possibility of using other renewable energy forms such as biodiesel and co-firing crop and wood residues to generate electricity.

In doing this we follow a number of previous studies and followed studies on:

- Life-cycle accounting as in Wang et al. [14] or Mann and Spath [15] doing our own analysis of GHG consequences;
- Ways agriculture might modify production patterns in the face of GHG mitigation alternatives as in Adams et al. [16], Callaway and McCarl [17], McCarl and Schneider [18], Antle et al. [19], Lewandrowski et al. [20,21], and U.S. EPA [22];
- Agriculture might alter production patterns in the face of higher energy prices as analyzed in Francl [23], McCarl et al. [24], USDA Office of the Chief Economist [75], Antle et al. [25], Konyar and Howitt [26], and Schneider and McCarl [27,28]; and
- Agriculture might react to biofuel activities Tyner et al. [29], McCarl et al. [30], Schneider and McCarl [28], Lee et al. [21], and U.S. EPA [22].

2. Ethanol fuel as a gasoline substitute

Ethanol is not a perfect substitute for gasoline and hence this section overviews the compatibility between these fuels. One of the most important properties for gasoline is a high vapor pressure. Vapor pressure is important for starting a cold engine, because some of the fuel has to vaporize easily and combusted in an engine ([31], pp. 86–89). From Table 1, pure ethanol has a lower vapor pressure than gasoline [32,33]. However, ethanol–gasoline blends have a complex vapor pressure relationship. E22 blends and below have a higher vapor pressure and easily evaporates into the atmosphere, thus these blends allow easy start up of engines [33,34,8,12]. However, the U.S. EPA sets a maximum vapor pressure for gasoline fuels. Blending ethanol with gasoline could increase vapor pressure above EPA's maximum. Consequently, gas distributors would have to purchase a more expensive lower vapor pressure gasoline in the summer, increasing gasoline costs[1] [12].

Octane rating is another important fuel property. Octane rating is a measure of how much pressure and temperature is needed to ignite the fuel/air mixture. A low-octane gasoline causes premature fuel ignition, which places stress on engine parts and in some cases could damage the engine ([31], pp. 90–95). From Table 1, pure ethanol has a higher octane level than gasoline. Moreover, petroleum refineries could reduce costs by producing a lower grade octane gasoline and mixing it with ethanol to increase octane rating [6,12,32].

Ethanol contains less energy than gasoline. The lower energy content reduces torque, acceleration, and miles per gallon [8,12]. Car manufacturers may have to increase fuel tank sizes to compensate. Researchers use two energy values. The higher heating value (HHV) is the combustion energy including the energy to vaporize water, while the lower heating value (LHV) only includes the combustion energy [4,35]. The lower heating value is used, because the energy from vaporized water performs no work in the engine. From Table 1, one gallon of ethanol contains from 65.5% to 67.9% less energy than one gallon of gasoline.

[1] Vapor pressure increases as the ambient temperature increases.

Table 1
Ethanol and gasoline fuel properties.

	Units	Gasoline	Pure ethanol
Octane number	100%	85–94	112.5–114
Reid vapor pressure	PSI	7.0–15.0	2.3
Higher heating value	BTU/Gal.	125,000	84,600
Lower heating value	BTU/Gal.	112,00–116,000	75,670–76,100

Sources: Davis and Diegel [77]; Gallagher et al. [12]; Reynolds [32]; Sheehan et al. [52].

Another restriction for ethanol is the current design of automobile engines. Ethanol could be blended with gasoline up to E15 without engine modification, whereas flexible fuel vehicles (which have modified engines) could use up to E85. (The "E" is for ethanol and the number refers to ethanol percentage by volume.) Thus at this time, ethanol could never completely eliminate gasoline as a fuel.

Ethanol has three more potential problems. First, ethanol–gasoline blends separate in the presence of water and are difficult to remix [8,12,36], making ethanol blends difficult to store and transport, especially through pipelines [37]. Second, ethanol–gasoline blends can degrade some types of rubber and plastics, and may degrade some engine seals, especially in the fuel system [8]. Finally, ethanol–gasoline blends dissolve carcinogenic substances from gasoline like benzene, toluene, ethylbenzene, and xylenes. The ethanol could steep from fuel lines at filling stations, carrying these substances with it potentially contaminating nearby soil. Moreover, ethanol–gasoline plumes tend to spread over a longer distance [8].

Despite some disadvantageous of using ethanol for a transportation fuel, it is also used as an oxygenate. The federal Clean Air Act Amendments (CAAA) of 1990 requires cities with high ozone concentrations or carbon monoxide emissions to add oxygenates to gasoline, because oxygenated gasoline have cleaner emissions [32,8,12,36,38].

3. Modeling approach

The agriculture sector is complex and highly interrelated. Previous analyses reveal a number of features that are needed in any analytical approach to reasonably assess biofuel production and associated GHG mitigation potential. Among these are as follows.

3.1. Biofuel production market and production interrelationships

Biofuel industry has impacts on other agricultural markets. For example, biofuel production levels influence cattle feeds for livestock production as well as how agricultural producers allocate land. This study utilizes an analytical approach that simultaneously depicts crop and livestock production, biofuel processing, the feeding of crop products to livestock, grazing, product substitution, competition for land, exports, imports and market price formation among other factors across the agricultural sector.

3.2. Representing ethanol production possibilities

Different technologies exist to produce ethanol. The differences involve the way sugar is separated and created from the feedstock.

3.3. Multiple gas implications

Each stage in agricultural production either release or sequester greenhouse gases. The greenhouse gases are carbon dioxide, nitrous oxide, and methane.

3.4. Co-benefits

Agricultural mitigation alternatives are frequently cited as win-win approaches as a number of the strategies generate GHG offsets while at the same time as achieving environmental quality gains in terms of reduced erosion and improved water quality.

3.5. Market/welfare implications

U.S. agriculture produces large quantities of a number of commodities relative to domestic needs and total global market volume. Variation in U.S. production influences prices in these markets. Thus it is possible that U.S. GHG mitigation policies will also affect domestic and world market prices along with the welfare of producers and consumers in those markets. The analytical approach used here includes a representation of domestic agricultural markets and their links to foreign markets.

The approach used to address these issues identified above is to simulate them in an agricultural model. The model used in this research is the Forest and Agricultural Sector Optimization Model Greenhouse Gas, hereafter referred to as FASOMGHG. This model has greenhouse gas accounting unified with a detailed representation of the possible mitigation strategies in the agricultural sector as adapted from Schneider [39], Lee [40] and McCarl and Schneider [18] in addition to a number of recent updates that have improved the depiction of biofuel production possibilities.

FASOMGHG is a mathematical programming, price endogenous model, and consists of approximately 120,000 variables, 800 non-linear variables, and 9500 constraints. FASOMGHG is written in the General Algebraic Modeling System (GAMS) and the solver, CPLEX, finds the optimal market prices and quantities. FASOMGHG uses the Law of One Price, where any price differences between markets originate from transportation costs. With a large number of markets, FASOMGHG accounts for the opportunity costs and byproducts of biofuel production [30,41].

The U.S. is divided into 63 agricultural production regions in FASOMGHG. Each region has unique climate and different economic opportunities. The producers in each region process the agricultural commodities into 56 primary crop and livestock products, which are listed in Table 2. Furthermore, the producers can process the primary commodities into 39 secondary products and shown in Table 3. The processing activities operate in 11 market regions and ethanol production could occur in any of these regions [30,41].

FASOMGHG includes an international sector and decomposes the world into 27 trade regions and U.S. trade depends on the commodity and region of the world. All the sugar and starch crops are imported and exported, except sugar beets. Moreover, ethanol and crop residues are not traded internationally and no international possibilities are included for these commodities [41].

4. Ethanol production possibilities

The technology determines which feedstocks are used and which byproducts are created. This section reviews the technology and how the markets are linked in FASOMGHG.

Table 2
Primary crops and livestock.

Category	Activity
Primary crops	Barley, citrus, corn, cotton, hay, oats, potatoes, rice, silage, sorghum, soybeans, sugar beets, sugarcane, tomatoes, and wheat
Energy crops	Hydrid poplar, switchgrass, and willow
Livestock	Beef cattle, dairy cattle, hogs, horses and mules, poultry, and sheep
Misc.	Eggs

Source: Adams et al. [41].

Table 3
Major secondary products.

Category	Activity
Animal products	Beef, chicken, edible tallow, non-edible tallow, pork, turkey, and wool
Bio-energy	Biodiesel, ethanol, and electricity
Corn wet mill	Corn oil, corn starch, corn syrup, dextrose, high fructose corn syrup, and gluten feed
Dairy products	American cheese, butter, cream, cottage cheese, ice cream, and milk
Potato products	Dried potatoes, frozen potatoes, and potato chips
Processed citrus products	Grapefruit and orange jc8uice
Refined sugar items	Refined cane sugar and refined sugar
Soybeans	Soybean meal and soybean oil
Sweetened products	Baking, beverages, confection, and canning

Source: Adams et al. [41].

Table 4
Corn wet mill possibilities.

Input	Output
1 bushel corn	31.5 lbs of starch or 2.5 gallons of ethanol and 1.5 lbs of corn oil and 2.6 lbs of corn gluten meal and 13.5 lbs of corn gluten feed
1 pound of starch	1.3 lbs of corn syrup or 1.19 lbs of dextrose or 1.41–1.54 lbs high fructose corn syrup (HFCS)

Sources: National Corn Growers Association 2007 [78]; Rausch and Belyea [79]; Light [73].
Note: HFCS comes in two types. The sweeter HFCS-55 is used in carbonated drinks while the less sweet HFCS-42 is used in everything else. The number indicates the percentage of fructose in the syrup.

4.1. Corn wet mill

The first technology is the corn wet mill and the production coefficients are shown in Table 4. The input is corn and the output is starch, corn oil, corn gluten feed, and corn gluten meal. The starch could be converted into corn syrup, dextrose, ethanol, or high fructose corn syrup. The analysis in this paper includes markets for all these products.

4.2. Dry grind possibilities

The second technology is the dry grind production budgets for barley, corn, sorghum, oats, rice, sugar beats, sugarcane, sweet sorghum, and wheat. The dry grind has two chemical processes which are sugar and starch fermentation.

Sugar fermentation process converts simple sugars into ethanol using the chemical reaction as shown in Eq. (1) [42,6]. If all sugar is converted into ethanol, then 1 ton of pure sugar theoretically yields 154.9 gallons of ethanol. The theoretically yield will be adjusted to reflect the practical yield in the industry. Further, this conversion applies to sugar extracted from sugarcane, sugar beets, and sweet sorghum. The chemical conversion is approximate, because density changes with temperature.

$$\underset{180\,\text{kg}}{C_6H_{12}O_6} \rightarrow \underset{92\,\text{kg}}{2C_2H_5OH} + \underset{88\,\text{kg}}{2CO_2} \qquad (1)$$

Starch fermentation is similar to sugar fermentation. Starch is a polymer and is composed of molecules that are similar to glucose. The molecules can link linearly and is called amylase, or the molecules can form branches and is called amylopectin. Both amylase and amylopectin are summed collectively as starch. A hydrolysis reaction causes the starch to react with water, creating a solution of glucose. Hydrolysis uses either an enzyme or acid to facilitate the reaction [6,43]. One kilogram of starch yields theoretically 1.11 kg of glucose[2] [44,45]. Thus, 1 ton of pure starch theoretically yields 172.0 gallons of ethanol.

Table 5
Theoretical ethanol chemical yields.

Source	Fermentation type	Sugar or starch content%	Theoretical ethanol yield gal/ton of feedstock
Barley	Starch	50.0–55.0	86.0–94.6
Corn	Starch	72.0	123.8
Grain sorghum	Starch	67.0–73.8	115.2–126.9
Oats	Starch	64.0	110.1
Pure sugar	Sugar	100.0	154.9
Rice grain	Starch	74.5	128.1
Sugar beet	Sugar	16.0–17.3	24.8–26.9
Sugarcane	Sugar	10.0–12.0	15.5–18.6
Sweet sorghum	Sugar	13.0	20.1
Wheat	Starch	57.9	99.5

Sources: Agricultural Research Center 2005 [80]; Committee on Animal Nutrition, Board on Agriculture and Renewable Resources, Commission on Natural Resources, and National Research Council [46] p. 16; Food and Agricultural Organization 2002 [34]; Gnansounou et al. [81]; Haley et al. [82]; Pardee [45]; Stenzel et al. [53]; Wallace et al. [83]; Xie et al. [84].
Note: Some starch feedstocks may contain trace amounts of sugar.

The theoretical chemical yields are shown in Table 5 and contains the feedstock source, whether the feedstock uses starch or sugar fermentation, the sugar or starch content, and the theoretical ethanol yield from 1 ton of feedstock.

The ethanol chemical yields are lower than the theoretical yield, due to extraction, conversion, and recovery efficiencies. The extraction efficiency is the amount of sugar or starch that can be extracted from the feedstock given current technology and is shown in Table 6. The conversion efficiency is the percentage of sugar that is chemically converted to ethanol. Research indicates the conversion efficiency ranges from 92 to 92.5% ([42,45]). The recovery efficiency is the percentage of ethanol that can be recovered from the chemical mixture. The recovery efficiency is set at 99%, because ethanol uses the two-stage distillation process. The first stage distills ethanol to a 95.6% concentration ([46] p. 11; [4]), while the second stage uses denaturants, desiccants, or molecular sieves to remove the remaining water [6].

The practical ethanol chemical yields are shown in Table 6 with the extraction efficiencies, amount of Distillers Dried Grains with Solubles (DDGS) produced, and technological growth rate. The extraction efficiencies are either from the literature or calculated from known chemical yields in the literature. DDGS is the yeast and crop residues leftover from the fermentation. DDGS is a high-protein source that can be blended with animal feeds and sold to the animal feed markets. DDGS is included in the agricultural model. The derivation of the technological growth rate is described in Section 4.4.

The ethanol industry also produces CO_2 as a byproduct [42,6]. The food industry uses liquefied CO_2 to freeze, chill, and preserve food, or uses CO_2 to carbonate beverages. FASSOMGHG does not include a CO_2 market, because a large ethanol industry could easily saturate the CO_2 market, causing the market price to drop significantly. The CO_2 market was 5.6 million tons in 1995 with a 3–4 percent per year growth rate [47]. An ethanol industry with 36 ethanol refineries with production capacity of 50 million gallons per year could supply this market. However, the CO_2 emissions were included the life-cycle GHG emissions.

4.3. Lignocellulosic fermentation

The last technology is lignocellulosic fermentation, which uses crop residues for the input. Crop residues do not have an official

[2] The biorefinery does not create matter. The increased mass resulted from the chemical reaction between starch and water.

Table 6
Extraction efficiencies, chemical yields, DDGS for feedstocks, and technology.

Feedstock	Extraction efficiency %	Ethanol yield Gal./ton of feedstock	DDGS lbs/Gal. of ethanol	Technological growth rate %/year
Barley	89.5	70.1–77.5		0.311
Corn (dried grind)	86.9	98.0–98.6	5.9–6.1	0.409
Corn (wet milled)	78.8	88.8–89.3	–	0.738
Grain sorghum	78.0–90.4	81.8–105.1	7.9	0.279
Oats	89.5	89.7–90.2	9.9	0.311
Pure sugar	100	141.1–141.9	–	–
Rice grain	89.5	104.5–105.0	5.3	0.277
Sugar beet	87.9	19.8–21.6	14.2	0.372
Sugarcane	93.1–97	15.5–18.6	14.9	0.181
Sweet Sorghum	86.9	15.9–16.0	7.9	0.410
Wheat	95–97.3	86.1–88.7	7.3–9.2	0.033

Sources: Haley et al. [82]; Kim and Dale [50]; Raush and Belyea [79]; Stenzel et al. [45]; Sweden Biobase [53]; Szulczyk [84]; Wallace et al. [85]; Xie et al. [86].
Note: Barley, oats, and rice grain use the average extraction efficiency for starch crops.

Table 8
Extraction, conversion, and recovery efficiencies.

Sugar	Extraction efficiency %	Conversion efficiency %	Recovery efficiency %
Arabinose	75–90	59–90	99
Galactose	82	90	99
Glucose	50–90	92–92.5	99
Mannose	89	90	99
Xylose	75–90	59–92	99

Source: Hamelinck et al. [42].
Note: The extraction efficiency is unknown for arabinose, thus the xylose efficiency is used.
Note: Extraction efficiencies are based on acid hydrolysis.

market, but they serve two purposes in the agricultural model. First, crop residues provide surface cover that prevents soil erosion and provides nutrients and organic matter for the soil, which are critical for future crop yields [48–53]. Thus, FASOMGHG restricts the amount of crop residues that can be removed from the land. Second, crop residues could be co-fired with coal to generate electricity, which is also included in FASOMGHG. FASOMGHG contains lignocellulosic production possibilities for bagasse, barley, straw, corn stover, oat straw, rice straw, sorghum straw, and wheat straw.

Lignocellulosic fermentation is more complex than sugar/starch fermentation. Plant residues contain cellulose and hemicellulose. Cellulose is the largest component and is composed of glucan, while hemicellulose is composed of arabinan, galactan, mannan, and xylan. These five components can be broken down into two categories of sugar using either an acid or enzyme hydrolysis. The sugar category refers to the number of carbon (C) atoms contained in the sugar molecule. The C6 sugars are glucose, galactose and mannose, which originate from glucan, galactan and mannan, while the C5 sugars are arabinose and xylose, which originate from arabinan and xylan. Microorganisms can ferment all sugars into ethanol. The variety of sugars requires multiple processing stages, increasing capital and operating costs [42,34,7,54,55,52].

The composition of crop residues is shown in Table 7. The C6 polymers are similar to starch, whereas 1 ton of glucan, galactan, or mannan yields 1.11 tons of C6 sugars [56] and could be fermented theoretically into 172.0 gallons of ethanol. One ton of arabinan or xylan yields 1.14 tons of C5 sugars [56] and could be fermented theoretically into 176.0 gallons of ethanol. The reaction is similar to Eq. (1). The feedstock also contains lignin, which is a fiber. Lignin has to be removed, because it interferes with the fermentation process [42].

The extraction, conversion, and recovery efficiencies cause the ethanol chemical yields to be lower than the theoretical. The efficiencies are defined similarly as the sugar and starch fermentations and are listed in Table 8 for each sugar.

The ethanol industry does not currently use lignocellulosic fermentation. However, the practical ethanol chemical yields are shown in Table 9 and include the impact of the three efficiencies from Table 8. The mid-range values are used for the FASOMGHG. The mid-range values are close to what is cited in the literature and are included in Table 9 for a comparison. The crop residue to crop ratio and technological growth rates are also included in Table 8 and are explained in Section 5.

Lignin is produced from lignocellulosic fermentation as a byproduct and could be burned to produce electricity and heat in FASOMGHG. The high heating value (HHV) is used to calculate the heating value for lignin, because the vaporization of water performs work in an electric generating facility. Each ton of lignin with 33% moisture content yields 18,222,000 BTUs of heat energy [57]. The efficiency for lignin-electricity generation starts with a 32% energy efficiency [58]. The energy efficiency is the percentage of heat energy that is converted to electricity.

FASOMGHG does not contain the following byproducts for lignocellulosic fermentation: CO_2, furfural, gypsum, and biogas. The reason is because these markets are small, and a large ethanol industry would cause the market price to fall. Further, these byproducts could require expensive capital upgrades. Carbon dioxide is released from the fermentation process and this CO_2 is included in the life-cycle emissions. Furfural is created from the breakdown of hemicellulose, and could be used to make carpet fibers [49,54]. Gypsum is a byproduct from neutralizing the acid used in hydrolysis [59,42]. Finally, biogas is created from anaerobic fermentation in the biorefinery's wastewater and contains 75% methane. An ethanol refinery could collect and burn this gas for heat and electricity [59,42,34,53,54,60].

4.4. Incorporating technological progress

High energy prices and GHG prices are likely to induce technical change where ethanol production yields given an amount of feedstock, feedstock yields per acre and the cost of ethanol processing are likely to change over time particularly for cellulosic ethanol. In our framework these are depicted by having:

Table 7
Crop residue composition.

Feedstock	Glucan wt%	Galactan wt%	Mannan wt%	Arabinan wt%	Xylan wt%	Lignin wt%	Theoretical chemical yield Gal/ton of feedstock
Bagasse	40.6	0.8	0.2	1.7	20	25.5	109.7
Corn stover	40.9	1	0	1.8	21.5	16.7	113.1
Rice straw	34.2	0	0	0	24.5	11.9	101.9
Sorghum straw	34.01	0.52	0.2	1.65	14.1	16.1	87.4
Wheat straw	38.2	0.7	0.3	2.5	21.2	23.4	109.1

Sources: Energy Efficiency and Renewable [87], Kadam [7], Kim [88] p. 33, Tshiteya and Tshiteya [55].

Table 9
Ethanol chemical yields.

Feedstock	Crop residue to crop ratio	Practical ethanol chemical yield Gal./ton of feedstock	Ethanol chemical yields from Literature Gal./ton of feedstock	Tech. growth rate %/year
Bagasse	0.60	49.80–90.07	67.2–71.88	1.15
Barley straw	1.20		60.00–74.4	1.15
Corn stover	1.00	51.25–92.78	56.5–79.2	1.15
Oat straw	1.30		60.00–62.4	1.64
Rice Straw	1.35–1.40	45.67–83.81	60.00–67.2	1.16
Sorghum straw	1.30	39.70–71.79	64.60–64.8	1.15
Wheat straw	1.30	49.47–89.54	57.6–70.00	1.15

Sources: Kadam et al. [89]; Kadam and McMillan [49]; Kim and Dale [50]; Mann and Bryan [90]; Sheehan et al. [52]; Wallace et al. [53]; White [91].
Note: Barley straw and oat straw use the wheat straw chemical yields and technological growth rate, because they are in the grass family.

- Crop yields increase over time at rates forecasted by USDA [61].
- Ethanol yields increasing over time where ethanol producers are assumed to attain 90% of theoretical chemical yield in 30 years, where the conversion, extraction, and recovery efficiencies result in a total efficiency of 90%. The annual growth rates are shown in Tables 6 and 9.
- The efficiency for lignin-electricity generation increases to 42% [58], increasing 1.09% annually. The 42% energy efficiency occurs as producers upgrade or build new electric generation facilities.

Technological improvement can also be incorporated by having production costs decrease over time or genetic engineering improves sugar/starch content in crops. However, these alternatives were not examined because this paper is already quite lengthy.

4.5. Greenhouse gas efficiency

Researchers like Pimentel [62] and Searchinger et al. [63], have criticized ethanol for being energy and GHG inefficient. However, the GHG emissions and energy efficiency not only depend on the production and consumption of ethanol, but also on ethanol's byproducts and inputs. For example, crops absorb carbon from the atmosphere and energy from the sun. As producers convert plants into fuel, they release greenhouse gases and consume energy. The producers harvest, haul, ferment, and distill the feedstock into ethanol, and then combust the ethanol in a car engine. Thus, energy and GHG efficiency depends on ethanol conversion rates, crop yields, fertilizer manufacturing and application, byproduct analysis, and amount of energy used in each process [35,64]. For example, life-cycle analysis includes byproducts like DDGS that displaces corn in feeding and thus the attendant GHG emissions and energy inherent therein. Thus, FASOMGHG accounts for these GHG emissions and allows producers to alter their activities as if there was a carbon equivalent price.

Biofuels are not equal in their GHG efficiency and creating an institution of a GHG emission-based cap and trade system will allow biofuel production to move towards more GHG efficient forms. Estimates of ethanol GHG efficiency from various feedstocks considering GHGs used in crop production, manufacturing of crop production inputs, hauling of feedstocks, processing plant transformation and byproduct offsets are given in Table 10. These results show among other things that the current major U.S. source of ethanol—corn is relatively GHG inefficient while sugarcane and cellulosic ethanol sources are much more efficient. In addition one should note that this does not account for indirect land use or offsite leakage as discussed in Murray et al. [74], Searchinger et al. [63] or Fargione et al. [65].

5. Economic cost of ethanol production

Total ethanol production cost can be broken into two main components: feedstock procurement and plant construction/operation. The feedstock procurement costs include feedstock costs and hauling costs, while the plant construction/operation costs include production costs, capital costs, and transportation costs.

Feedstock costs are an opportunity cost of diverting land and adding inputs to provide feedstocks for ethanol production. These costs are endogenous and determined in FASOMGHG. Further, we also use basic budget data on the cost of producing feedstocks in terms of fertilizer, seeds, equipment, planting and harvesting.

Table 10
Percentage offset of net GHG emissions from the usage of a Biofeedstock.

Feedstock commodity	Form of bioenergy				
	Liquid fuels			Electricity	
	Crop ethanol (%)	Cellulosic ethanol (%)	Biodiesel (%)	Co-fire at 5% (%)	Fire with 100% biomass (%)
Corn	30.5				
Hard red Win. wheat	31.5				
Sorghum	38.5				
Sugarcane	64.8				
Softwood residue		80.0		99.2	97.4
Hardwood residue		79.9		99.0	96.5
Corn residue		75.1		93.7	88.1
Sugarcane bagasse		90.1		100.0	100.0
Wheat residue		73.8		95.6	91.4
Switchgrass		68.6		94.3	89.5
Hybrid poplar		61.9		94.1	89.1
Willow		67.7		96.6	93.7
Lignin				91	86
Cattle manure				99.6	96.5
Soybean oil			70.9		
Corn oil			55.0		

Table 11
Feedstock hauling costs and parameters.

Feedstock	b_0 ($)	b_1 ($ per mile)	Load size (tons)
Barley	45	1.10	60
Corn (dry grind)	45	1.10	60
Corn (wet mill)	45	1.10	60
Crop Residues	90	2.20	20
Oats	45	1.10	60
Pure sugar	90	2.20	25
Rice	45	1.10	60
Sorghum	45	1.10	60
Sweet sorghum	90	2.20	20
Wheat	45	1.10	60

Note: The hauling costs also include preparing feedstocks for use.

Table 12
Economic costs of ethanol production in 2000 dollars.

Type	Wet mill ($ per gallon)	Dry grind ($ per gallon)	Lignocellulosic ($ per gallon)
Feedstock costs	Endogeneous	Endogeneous	Endogeneous
Hauling costs	Endogeneous	Endogeneous	Endogeneous
Operating costs	$0.46	$0.3958	$1.31
Capital costs	0.1165	0.0832	0.315
Transportation and storage costs	0.05	0.05	0.05

Sources: Energy Information Administration 2007 [92], Shapouri and Gallagher [93], Wallace et al. [53].

The hauling costs are regionally dependent and a function of crop yields, using a formula developed by French [66]. He assumed a biorefinery is located in a center of a circular region, surrounded by a square grid layout of roads and thus, the hauling cost is given by the Eq. (2). The formulae compute the average distance that the feedstock is hauled of $\bar{D}$ miles where S is the amount of feedstock required for the biorefinery in tons, Y is the crop yield per acre in tons, Z is the crop density in terms of proportion of land in the service area devotes to that crop, and 640 is an acres-per-square-mile conversion. The hauling costs per ton of feedstock is defined as H, where b_0 is the fixed loading charge, b_1 is the rate charge, L is the truck load size, and the 2 indicates two way travel. The hauling costs parameters are defined in Table 11. Even though the ethanol production budgets have fixed capital (fixed S), hauling costs are updated in the FASOMGHG to reflect changes in crop yields and density, because these differ by region and time.

$$\bar{D} = 0.4714\sqrt{\frac{S}{640YZ}} \quad \text{and} \quad H = \frac{b_0 + 2b_1\bar{D}}{L} \tag{2}$$

The construction/operating costs are defined for three refinery types ethanol dry grind refineries, ethanol wet mill, and ethanol lignocellulosic, and are shown in Table 12. Operating costs include labor, materials, insurance, utilities, and taxes. The operating costs for co-firing lignin with coal by co-fire percentage are shown separately in Table 13. FASOMGHG has production budgets for burning 100% lignin, or co-firing the lignin with coal from 5% to 20%. Lignin contains little sulfur and co-firing with coal can reduce sulfur dioxide emissions, lowering the need to purchase sulfur dioxide credits. However, at this point, sulfur dioxide credits are not included.

Table 13
100 MW per year production and capital costs for lignin-electricity generation.

Type	Production costs ($)	Capital costs ($)
Pure lignin	13,363,330.00	45,625,000
5% lignin co-fire	51,486.40	1,573,880
10% lignin co-fire	101,134.00	3,200,320
15% lignin co-fire	154,459.20	4,882,240
20% lignin co-fire	209,623.20	6,621,100

Sources: Hughes [94]; Markiewicz et al. [95]; Qin et al. [96].

The lignocellulosic facilities and sweet sorghum biorefinery capacity is fixed at 20 million gallons, while the other refineries are assumed to be 40 million gallon facilities. The capital budgets were derived from [67] and Wallace et al. [53]. The assumption is capital has a 10-year life with a discount rate of 8%. Using continuous compounding, the real capital depreciation cost is $0.0832 per gallon for the dry grind, $0.1165 for the wet mill, and $0.315 per ethanol gallon for lignocellulosic fermentation. The capital costs for electricity generation are shown in Table 13. The capital cost for burning 100% lignin to create electricity is the whole 100 MW generating facility, while for co-firing, the capital is the upgrade to equipment that process and feed the lignin to the steam boilers. Moreover, the electric and ethanol facilities are assumed to be located near each other.

The last cost is transporting the ethanol to the retail market. The ethanol refinery transports ethanol by truck to petroleum product terminals and ethanol is stored in its own tank. When ethanol is ready to be transported to the retail market, it is blended with gasoline and transported by truck. Consequently, this analysis uses a real cost of 5 cents per gallon to transport and store the ethanol [12].

6. Ethanol market penetration

FASOMGHG is used to predict the U.S. market penetration for ethanol and the costs of feedstocks. Two important assumptions are made about market penetration. First, the gasoline markets remain the same size. Thus, any increases in ethanol production reflect increased market penetration. Second, no problems are encountered when the ethanol is blended with petroleum-based fuels, such as gasoline–ethanol blends exceeding E15.

Ethanol producers receive federal and state subsidies. The state subsidies vary, but the federal ethanol subsidy is $0.51 per gallon [68,69]. The production period ranges from 2000 to 2030 with 5-year increments. The wholesale gasoline price is exogenous and ranges from $1.00 to $4.00 per gallon, using the 25-year energy price forecasts from the National Energy Modeling System [70]. Further, the ethanol price is adjusted for the lower energy content of the fuel. FASOMGHG is used to examine three scenarios: varying fossil fuel prices, carbon equivalent price for greenhouse gases, and the removal of U.S. federal government subsidies.

6.1. Varying energy prices

FASOMGHG predicts the U.S. ethanol market penetration as shown in Fig. 1. The U.S. production is in millions of gallons and the ethanol price is adjusted for the lower energy content. FASOMGHG clearly shows that ethanol producers supply approximately the same level of ethanol production independent from the gasoline price. The reason is gasoline prices raise both revenues from ethanol and feedstock costs. The estimated ethanol production is approximately 75 billion gallons of equivalent fuel in 2030, when gasoline is $4 per gallon. With an annual U.S. gasoline supply of approximately 142.4 billion gallons in 2007 [71], U.S. ethanol production attains a maximum predicted market penetration of 53%.

FASOMGHG predicts the sources for ethanol as shown in Fig. 2 when the gasoline price is set at $2 per gallon and quantity is in millions of gallons of ethanol. The primary source of ethanol is from the corn wet mills, because the wet mills produce other valuable byproducts like corn oil, which can produce biodiesel. The second largest ethanol source quickly grows over time and uses lignocellulosic fermentation from bagasse, corn stover, and soft

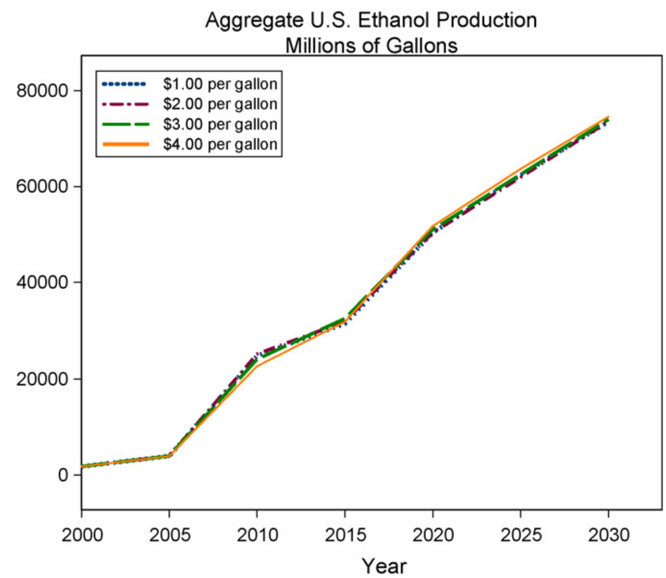


Fig. 1. Aggregate ethanol production.

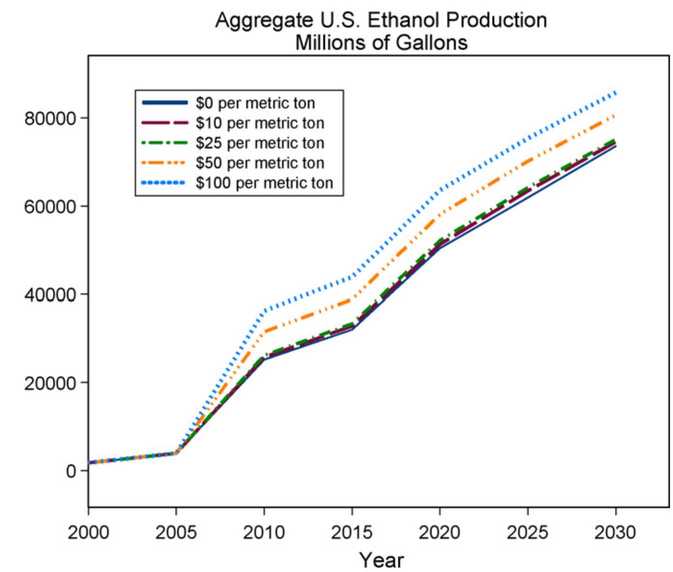


Fig. 3. Aggregate ethanol production for various carbon equivalent prices.

wood pulp. Ethanol producers also use some energy crops, such as hybrid poplar and switchgrass. Unfortunately, ethanol produced from the dry grind industry does not show any increase over time. The feedstocks are barley, wheat, sorghum, and sweet sorghum, which are also used in the animal feeds and/or human food.

6.2. Varying GHG offset prices

FASOMGHG was used to predict the market penetration of ethanol given if a market price existed for GHG emissions. The GHG price uses the IPCC 100-year Global Warming Potential (GWP) as an exchange rate among GHGs ([72], pp. 726–771). The GWP defines carbon dioxide equals 1, methane as 21, and nitrous oxide as 310 ([41], p. 114; [7]). The carbon equivalent price ranged from $0 to $100 per metric ton, because Schneider and McCarl [27] have shown this price range to be effective in reducing greenhouse gas emissions.

The model predicts the U.S. aggregate ethanol production for various carbon dioxide equivalent prices. The results are shown in Fig. 3 and the gasoline price was fixed at $2 per gallon. FASOMGHG predicts all ethanol production time paths are increasing and a carbon equivalent price has an expansionary impact on this industry. Additionally, the feedstock sources change with a carbon price. A higher carbon equivalent price boosts the corn wet mill industry, because this industry supplies corn oil which is used to produce biodiesel. However, carbon equivalent prices are ambiguous for lignocellulosic ethanol. Lignocellulosic feedstocks like crop residues and energy crops like hybrid poplar, switchgrass, and willow can also be co-fired with coal to generate electricity. FASOMGHG switches the feedstocks between the ethanol and electricity industries, because both are quite GHG efficient.

6.3. Federal subsidies

Subsidies for ethanol (and biodiesel) are set to expire on ethanol in December 2009. Consequently, FASOMGHG was used to predict the U.S. market penetration for ethanol, if U.S. government subsidiaries were removed. The results are shown in Fig. 4. Without question, the U.S. government subsidies expand the

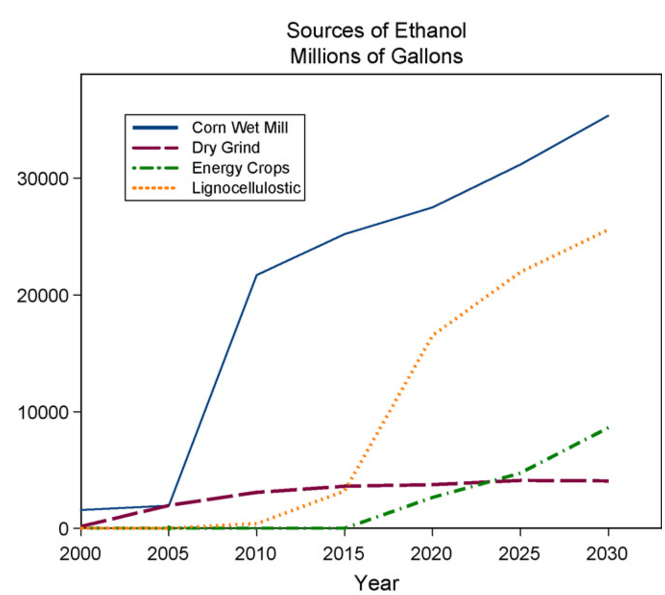


Fig. 2. Sources of ethanol.

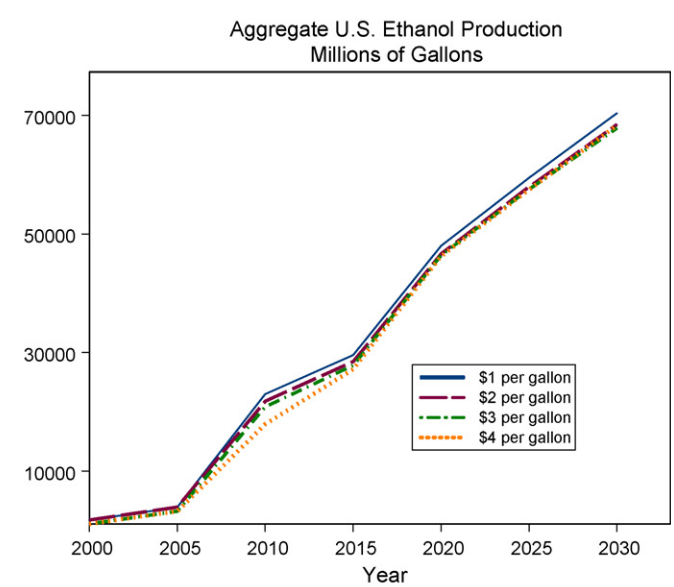


Fig. 4. Aggregate ethanol production with no government subsidies.

ethanol industry. If the $0.51 subsidy is removed, FASOMGHG predicts in 2030 that ethanol industry produces 3 billion less gallons of ethanol for low gasoline prices and 6 billion gallons less for high gasoline prices. The predicted maximum ethanol production is approximately 75 billion equivalent gallons and occurs in 2030 when the gasoline price is $4 per gallon, resulting in a market penetration of 52%. Thus, U.S. federal subsidies help expand the market penetration by approximately 1% in 2030.

7. Conclusions

This research indicates the ethanol can become an important source for a transportation fuel. However, the predictions from FASOMGHG are optimistic, because the price for gasoline is fixed at one level. Thus, producers have no uncertainty about the future price of fossil fuels. Further, for ethanol to become important, several problems have to be overcome:

- All cars sold in the United States will have to be flexible fuel vehicles. Otherwise, the ethanol industry could not supply more than 21 billions gallons of ethanol, which is 15% of the current U.S. gasoline consumption.
- The ethanol industry will have to develop an additive that prevents gasoline and ethanol blends from separating when contaminated with water. This would allow ethanol to be transported through pipelines and reduce storage costs.

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